ARCHITECTURAL SYSTEM INCORPORATING A HYPERSTRUT SPINE

Field of the Invention

This application relates generally to architectural systems and more particularly to node and strut configurations.

Background of the Invention

Despite the many advances in materials over the past several decades, and the continuing interest in alternative building styles such as dome structures, the use of spaceframes in construction continues to be rather limited. Although node and strut systems have been devised and used by some, only very limited types of geometries, generally those based on the cube or pyramid, have achieved widespread use.

One noteworthy exception is the pioneering work of Steve Baer, who on 27 Mar. 1973 was issued U.S. Patent 3,722,153 ("Structural System"). The Baer patent teaches some advantageous systems of nodes and struts. Unfortunately, the teaching in the Baer patent is limited by the small variety of structures included. Another exception is the teaching in U.S. Patent 5,265,395 ("Node Shapes of Prismatic Symmetry for a Spaceframe Building System") issued 30 Nov. 1993 to Haresh Lalvani. The Lalvani patent teaches nodes and struts of various geometries, but does not teach any system for constructing rigid, elongated structures incorporating golden geometry.

Those skilled in the art have overlooked substantial benefits that might be achieved in economies of mass production, versatility, high rigidity, low weight and/or ease of assembly in architectural systems incorporating golden geometry. It is to these opportunities that the present invention is directed.

Summary of the Invention

A node-and-strut structure is made so as to include a "hyperstrut spine" of at least six similar "vertebrae," and more preferably at least seven or eight vertebrae. Applicant has ascertained that such structures permit a maximum structural diversity with a minimum component inventory. In a first apparatus embodying the invention, each such vertebra includes one "left-hand strut," one "right-hand strut," and one "primary" node rigidly engaging a proximal portion of the left hand strut and of the right hand strut. These vertebrae are arranged so that the primary nodes each intersect a primary axis, so that the left-hand struts are all (nominally) parallel with one another, and so that the right-hand struts are similarly all parallel with one another.

Bearing against and rigidly supporting each of the left-hand struts' distal portions is a respective "left-hand node." The left-hand nodes are positioned so that a left-hand axis passes through all of them, the left-hand axis lying in a baseplane with the primary axis. With (a strut axis of) each of the left-hand struts the left-hand axis forms a respective acute angle therebetween about equal to $j \times 20.9° + k \times 31.7° + m \times 36° + n \times 37.4°$, where j, k, m, and n are each an integer that is at least 0. (Angular quantities that are "about equal" in this document are rounded conventionally, and thus are within about 0.4° or 0.5°.) Similarly, bearing against and rigidly supporting each of the right-hand struts' distal portions is a respective "right-hand node." The right-hand nodes are positioned so that a right-hand axis passes through all of them, the right-hand axis parallel to (but outside) the baseplane. With (a strut axis of) each of the right-hand struts the right-hand axis forms a respective acute angle therebetween about equal to $p \times 20.9° + q \times 31.7° + r \times 36° + s \times 37.4°$, where p, q, r, and s are each an integer ≥ 0 also. It will be noted that because these angles are acute, $(k + m + n)$ and $(q + r + s)$ are both at most 2, so this is a restricted class of angles.

In a second embodiment, a method of the present invention includes a step of assembling a set of at least 6 to 10 vertebrae each including one left-hand strut, one right-hand strut, and one primary node assembled as described above. This is done so that a primary axis passes through each of the primary nodes, the primary nodes

each including at least 1% metal by weight, the left-hand struts all being nominally mutually parallel, and the right-hand struts all being nominally mutually parallel also. While similarly assembling the left-hand and right-hand nodes according to the first embodiment, additional struts and nodes are assembled into the structure so that each of the nodes couples to at least 3 or 4 struts that are not nominally coplanar. A triangulated structure made by this method is exceedingly strong and lightweight.

In a third embodiment, j=p=0 and the vertebrae have nominally irregular spacing. Also all of these nodes and struts are made primarily of a metal such as aluminum or an iron-containing alloy, preferably more than 50% by weight. All of the nodes preferably have at least a metallic bearing surface that extends inward or outward from the corresponding strut's axis so as to engage a counterpart metallic bearing surface on the node. Metal threading or other bearing structures of this type can provide structural-grade engagement, able to resist a longitudinal compression or tension of about 100 Newtons or more. As summarized in **Fig. 12,** this document includes examples of this embodiment in which k>0, in which m>0, and/or in which n>0.

In a fourth embodiment, j>0 and the vertebrae have nominally regular spacing. As summarized in **Fig. 12,** this document includes examples of this embodiment in which k=q=0, in which m=r=0, in which n=s=0, and/or in which n>0. The primary nodes each include at least 1% metal by weight, the struts primarily comprising a glued laminated timber or a hollow metal structure or a carbon fiber structure. For example, each can primarily comprise aluminum or an iron-containing alloy by weight.

In a fifth embodiment, the left-hand and right-hand struts of each of the vertebrae are each nominally aligned along a respective strut axis so as to define two intersecting strut axes that form such an angle therebetween that is nominally equal to (or complementary to) an acute angle of $b \times 20.9° + c \times 30° + d \times 31.7° + e \times 35.3° + f \times 36° + g \times 37.4°$, where b, c, d, e, f, and g are each an integer ≥ 0. Note that this acute angle given by the formula can be either the "primary angle" between the vertebra's struts or its complement. Several embodiments are identified below where b=g=0

and either $c > 0$ or $d > 0$. This fifth embodiment further includes a uniform number T of additional strut ends each bearing against a corresponding one of the left-hand nodes, where T is at least 4 or 5.

These and various other features as well as additional advantages which characterize the present invention will be apparent from a reading of the following detailed description and a review of the associated drawings.

Brief Description of the Drawings

Fig. 1 shows an apparatus of the present invention including a hyperstrut spine with seven similar vertebrae.

Fig. 2 shows in greater detail how each node can realistically be configured to engage each strut end in the embodiments of this disclosure.

Fig. 3 shows an isometric top view of a very light, rigid tower that is an embodiment of the present invention.

Fig. 4 shows the tower of **Fig. 3** in an oblique isometric (indirect side) view from just below a horizontal baseplane.

Fig. 5 shows one of the "cells" that is used to articulate the structure tower of **Fig. 4** explicitly.

Fig. 6 shows the cell that abuts that of **Fig. 5** from below in the tower of **Fig. 4.**

Fig. 7 shows the cell that abuts each instance of the cell of **Fig. 5** from below in the tower of **Fig. 4.**

Fig. 8 shows a cell that is an irregular tetrahedron that abuts one side face of the cell of **Fig. 5** at the top of each of the three legs of the tower of **Fig. 4.**

Fig. 9 shows a cell that is an irregular tetrahedron that is actually a mirror image of the cell of **Fig. 8.**

Fig. 10 shows a cell that is a pyramid having a base that is a parallelogram, the last cell that is used in describing the tower of **Fig. 4.**

Fig. 11 shows the tower of **Fig. 4** again so as to illustrate additional instances of the present invention within it.

Fig. 12 shows a chart with rows that each correspond with one instance of a hyperstrut spine of the present invention, as depicted in **Figs. 11&13.**

Fig. 13 shows a "hyper-triangle" of the present invention composed of three hyperstruts (legs) joined at three icosahedra (vertexes).

Fig. 14 shows a complex cell nominally corresponding to a sub-structure that occurs several times in the embodiment of **Fig. 13**.

Figs. 15-19 each shows another cell to further clarify the structure of **Fig. 13.**

Fig. 20 shows a flowchart of a method of the present invention.

Detailed Description

Although the examples below show more than enough detail to allow those skilled in the art to practice the present invention, subject matter regarded as the invention is broader than any single example below. The scope of the present invention is distinctly defined, however, in the claims at the end of this document.

Numerous aspects of spaceframe architecture that are not a part of the present invention (or are well known in the art) are omitted for brevity, avoiding needless distractions from the essence of the present invention. For example, this document does not include much detail about material selection or node design, except where the inventor has observed opportunities for a synergy. Neither does this document address the use of panels, although node-and-strut structures are typically used with "skinning" of some sort.

Definitions and clarifications of certain terms are provided in conjunction with the descriptions below, all consistent with common usage in the art but some described with greater specificity. A "node" is a knob-like structural element that supports one portion of each of several struts. A "strut" is an element used to brace or strengthen a framework by being able to resist a longitudinal compression or tension of about 100 Newtons. A "structural" strut is one that extends between two structural nodes. A "structural" node is an element that supports several struts not all aligned along co-planar axes. These definitions are used because node-and-strut "structures" that do not satisfy these criteria are generally weak or unstable.

First and second angular values are "nominally equal" or "about equal" if they are within about 0.4° or 0.5°. Two lines are "nominally parallel" if mere translation would let them intersect so as to form an angle nominally equal to 0°. A strut is "aligned along" an axis if the axis passes through a strut nominally parallel to the strut's length. A group of struts is "nominally mutually parallel" if the struts in the group are each aligned along a respective one of several parallel axes.

A "complete" strut is one that substantially surrounds its corresponding axis for the entire length between the nodes engaged by the strut. Such a strut will distribute an axial tension or compression on opposing sides of its axis. An arcuate or other "incomplete" strut, by contrast, will bow further away from the axis under axial compression. This greatly reduces the rigidity of the system, or necessitates a needless increase in strut weight. The struts depicted and discussed in this document are all preferably complete and hollow, as solid-strut embodiments of the present invention would be somewhat more massive without a commensurate increase in rigidity. Struts of the embodiments presented in this document can alternatively be constructed of a light fibrous material such as glued laminated timber, fiberglass, carbon fiber, or any of several other commercially available composite-material products.

Turning now to **Fig. 1,** there is shown an apparatus of the present invention including a hyperstrut spine **100**. Spine **100** includes a set of seven similar vertebrae **101** each including one complete left-hand strut **180,** one complete right-hand strut **190,** and one primary node **171.** Interleaved with the primary nodes along primary axis **121** are several inter-primary struts **107,** each of which is coupled to a corresponding pair of the primary nodes **171.**

Each left-hand strut **180** and right-hand strut **190** has a proximal end **181,191** and a distal end **182,192.** Each primary node **171** rigidly engages the proximal ends of its corresponding left-hand strut and right-hand strut. All of the primary nodes **171** intersect primary axis **121.** Each of the left-hand struts **180** is aligned along a respective left-strut axis **186,** the left-strut axes **186** all being mutually parallel. Each of the right-hand struts **190** is similarly aligned along a respective right-strut axis **196,** the left-strut axes **196** all being mutually parallel.

Several left-hand nodes **172** each intersect a left-hand axis **122** that lies in a baseplane **199** with the primary axis **121.** Similarly, several right-hand nodes **173** each intersect a right-hand axis **123** parallel to the baseplane **199** (but not within it). Left-hand axis **122** intersects each of the left-strut axes **186** so as to form an acute angle **185.** Acute angle **185** is about equal to $j\times20.9° + k\times31.7° + m\times36° + n\times37.4°$, where j, k, m, and n are all integers ≥ 0. Right-hand axis **123** intersects each of the right-strut axes **196** so as to form angles **194,195.** One of the complementary angles **194,195** is acute, and is about equal to $p\times20.9° + q\times31.7° + r\times36° + s\times37.4°$, where p, q, r, and s are all integers ≥ 0. Each of the nodes shown has a metallic surface **104** bearing (at least) axially against a respective metallic surface **105** of each respective strut end affixed to the node. These bearing surfaces **104,105** are configured to maintain engagement and resist axial compression and/or tension of at least 100 Newtons along the axis of the strut end.

Angle **197** is seen between (axes of) the left-hand strut **180** and the right-hand strut **190** of each vertebra. In spine **100**, either inter-strut angle **197** or its complementary angle **198** is nominally equal to an acute angle of $b\times20.9° + c\times30° + d\times31.7° + e\times35.3° + f\times36° + g\times37.4°$, where b, c, d, e, f, and g are each an integer ≥ 0. Note that $(c + d + e + f + g) \leq 2$ and $b \leq 4$ for any such acute angle, because any larger sum would correspond to an angle of 90° or larger.

Fig. 2 shows in greater detail how each node **210** can realistically be configured to engage each strut end **220** in the embodiments of this disclosure. The shapes and relative lateral dimensions (i.e. perpendicular to strut axis **215**) of nodes and struts in **Fig. 2** are realistic for architectural elements of a practical space frame construction material such as an alloy that is at least 5% iron or aluminum by weight. Such shapes and dimensions are merely schematic elsewhere in this document, convenient for showing hyperstrut elements.

In **Fig. 2,** a protrusion **230** at each hollow strut's end **220** has an axial compression surface **231** and an axial tension surface **232** that each protrude outward from strut axis **215** in a generally radial direction. (In full engagement, it will be noted that a bottom surface of chuck portion **240** comes into forceful compression with a top surface of node **210,** so that both of these surfaces will become axial

compression surfaces.) Node **210** has 62 threaded bores **260** (one on each surface of the polyhedron as shown) each having an axial compression surface **261** configured to bear axially against surface **231** of strut **220.** Each threaded bore also has an axial tension surface **262** configured to bear axially against surface **232** of strut **220.** Strut end **220** is constructed so as to cause the threaded protrusion to extend axially from chuck portion **240** when chuck portion **240** rotates clockwise with respect to strut body portion **250.** The threaded protrusion **230** similarly retracts axially when chuck portion **240** rotates counterclockwise. Generally similar retractable node/strut coupling designs are described in U.S. Patent 4,193,706, titled "Bolt Connections Between Tubular Rods and Junctions in Three-Dimensional Frameworks." Such couplings are commercially available, as of this writing, from Mero Structures of Menomonee Falls, Wisconsin, USA (www.mero.com). In a preferred embodiment of the present invention, each node similarly receives each strut of structural importance, the node's metallic surface bearing axially against those of the strut to form a rigid engagement. It will be understood that **Figs. 3,4,11&13** all depict simplified node/strut interfaces so as to focus on hyperstrut macro-structures without undue distraction.

Fig. 3 shows a top view of a very light, rigid tower **300** that is an embodiment of the present invention. It includes three diagonal legs **302,303,304** and a vertical mast having a pinnacle node **311.** **Fig. 3** is an isometric projection, a somewhat artificial view in which the size of objects is not dependent upon their distance from the viewer. For example, each of the shoulder nodes **472,473,474** of the mast conceals several nodes of the same size directly below it, as shall be apparent in the indirect side view **399** shown in **Fig. 4.**

Fig. 4 shows the tower **300** of **Fig. 3** in an (oblique isometric) indirect side view (see view **399** of **Fig. 3**) from just below horizontal baseplane **410.** Diagonal legs **302,303,304** support vertical mast **401** and extend to baseplane **410.** Baseplane **410** passes through node **411** and two others that are part of central mast **401.** Baseplane **410** also intersects node **402** of leg **302,** node **403** of leg **303,** and node **404** of leg **304.**

Vertical axis **492** extends through nodes **412** and **472** and 5 nodes in between. Vertical axis **493** extends through nodes **413** and **473** and 5 nodes in between. Vertical axis **491** extends through node **411** and **471** and 5 nodes in between. These axes are helpful for identifying elements of the present invention within the embodiment of tower **300. Fig. 4** shows seven substantially parallel left-hand struts that include strut **480,** which is coupled to primary node **471** at its proximal end and to node **472** at its distal end. Also shown are seven substantially parallel right-hand struts that include strut **490,** which is coupled to primary node **471** at its proximal end and to node **473** at its distal end. Node **471** is the top one of seven collinear primary nodes aligned along axis **491.** Each of these primary nodes is rigidly affixed to a respective one of the left-hand proximal ends and a respective one of the right-hand proximal ends. Each of these 14 proximal ends forms an acute angle with axis **491** that is about equal to $p \times 20.9° + q \times 31.7° + r \times 36° + s \times 37.4°$, where p, q, r, and s are all integers. In this example, $p=q=r=0$ and $s=1$ for strut **480** (and the 6 similar left-hand struts) and strut **490** (and the 6 similar right-hand struts).

Node **472** is the top one of seven left-hand nodes aligned along axis **492.** Node **473** is the top one of seven right-hand nodes aligned along axis **493.** Axes **491** and **492** are parallel and lie in a common vertical baseplane, which is parallel to (and not coplanar with) axis **493.**

Fig. 5 shows one of the "cells" that is used to articulate the structure of the tower **300** of **Fig. 4** explicitly. Other than **Fig. 14,** each cell in this document is a simple convex polyhedron that has an edge that coincides with most or all of the struts in a part of a structure. Each face of a cell is a polygon having angles between its edges that coincide with angles that are formed between struts of the structure. For example, cell **500** is a tetrahedron having a base **510** that is an equilateral triangle. Cell **500** also has three side faces, each of which is an isosceles triangle with a 63.4° angle at the pinnacle point **511** and two 58.3° angles adjacent to base **510.** Four instances of cell **500** occur in tower **300,** one at the top of mast **401** and one at the top of each of the legs **302,303,304.**

Fig. 6 shows the cell **600** that abuts cell **500** from below in the tower **300** of **Fig. 4.** More particularly, in the topmost instance of cells **500&600** of tower **300,** top **610**

coincides with base **510.** Top **610** and bottom **620** of cell **600** are both equilateral triangles. The definition of cell **600** is completed by further specifying that the six side faces **630** are all isosceles triangles each having one 63.4° angle and two 58.3° angles. Note that three of the edges of cell **600** are hidden (behind), as indicated by the dashed lines. The bottom angle of the dashed triangle is 63.4°, as can be inferred by its opposite angle labeled at the very bottom of **Fig. 6.** Instances of cell **600** occur seven times in central mast **401** of tower **300.**

Fig. 7 shows the cell **700** that alternates between instances of cell **600** in the tower **300** of **Fig. 4.** More particularly, in the topmost instance of cells **600&700** of tower **300,** bottom **620** coincides with top **710.** Top **710** and bottom **720** of cell **700** are both equilateral triangles. The definition of cell **700** is completed by further specifying that the six side faces **730** are all isosceles triangles each having one 36° angle and two 72° angles. The tall hidden triangle at the rear-most face of cell **700** as seen in **Fig. 7** has two 72° angles at its base. All triangles have three interior angles having a sum of 180°, a fact which confirms that the top angle of the rear-most face of cell **700** is 36°. Instances of cell **700** occur six times in central mast **401** of tower **300.**

Fig. 8 shows cell **800,** an irregular tetrahedron that abuts one side face of cell **500** at the top of each of the three legs **302,303,304** of tower **300.** Oriented as shown in **Fig. 8,** cell **800** has an orientation that corresponds with a component of front leg **302,** as can be confirmed by a comparison with **Fig. 4.** The left rear (hidden) face of **Fig. 8** has a top angle of 31.7°, a left middle angle of 69.1 °, and a bottom angle of 79.2 °. The right rear (hidden) face of **Fig. 8** has a top angle of 63.4°, a bottom left angle of 58.3°, and another 58.3° angle on the right side. The top (front) face of **Fig. 8** has a top middle angle of 58.3°, a bottom left angle of 58.3°, and a bottom right angle of 63.4°. The bottom (front) face **810** of **Fig. 8** has a top left angle of 79.2°, a top right angle of 31.7°, and a bottom middle angle of 69.1°.

Abutting bottom face **810** of **Fig. 8** is an instance of top (hidden) face **910** of **Fig. 9.** (Top face **910** accordingly also has angles of 79.2°, 31.7°, and 69.1° as shown.) **Fig. 9** shows cell **900,** an irregular tetrahedron that is actually a mirror image of cell **800** across the plane of face **810.** Of particular interest is (hidden) face **920,** which has

angles of 69.1°, 79.2°, and 31.7° as shown. Six instances of cell **900** occur in each of the legs **302,303,304** of tower **300,** interleaved with five instances of cell **1000** of **Fig. 10.**

Cell **1000** is a pyramid having a base that is a parallelogram with interior angles of 69.1° and 110.9°. Adjacent to the two larger interior angles is the 63.4° angle of an isosceles triangle (face) that has two other interior angles of 58.3°, as shown. Each instance of (front) right-side face **1010** of cell **1000** abuts left-side (hidden) face **920** of cell **900.** Each instance of bottom-side (hidden) face **1020** of cell **1000** abuts a top-side (hidden) face **910** of cell **900.** Tower **300** of **Fig. 4** contains a total of 15 instances of cell **1000,** five being in each of the legs **302,303,304.**

Fig. 11 shows tower **300** again so as to illustrate additional hyperstrut spines of the present invention within it. Recall from the above description of **Fig. 4** that struts **480** and **490** extend between nodes on vertical axes **491,492,493,** forming angles with axis **491** of about 37.4° (e.g., for j=k=m=p=q=r=0 and n=s=1). Node **471** couples with both struts **480,490,** forming an angle of 63.4° between them (see **Fig. 6**).

Recall that strut **480** is designated as a "left-hand" strut and strut **490** is designated as a "right-hand" strut. Then tower **300** contains exactly seven such primary nodes that each couple to one left-hand proximal strut end and one right-hand proximal strut end, where the left-hand struts are all substantially parallel and the right-hand struts are all substantially parallel. Such a structure defines a spine having seven vertebrae. Let the number of such vertebrae for a given hyperstrut spine be the "count" of the spine. A structure of the present invention preferably has a count of at least 6, and more preferably has a count of at least 7 or 8.

Another optional property of some hyperstrut structures is "regularity." As used herein, a "regular" hyperstrut structure is one in which the vertebrae as described above are distributed with nominally uniform spacing. As summarized below in **Fig. 12, Fig. 13** contains some "regular" structures and some "irregular" structures. It is evident from an examination of **Figs. 1&11,** however, that all of the hyperstrut spines identified in those figures are "regular." The concept of a "count" and a "regularity" of a given hyperstrut spine will be clarified further by the examples that follow.

Referring again to **Fig. 11,** note that struts **1111** and **1112** also extend between nodes on vertical axes **491,492,493,** forming angles with axis **491** of about 20.9° (e.g., j=p=1 and k=m=n=q=r=s=0). Thus it can be seen that mast **401** contains exactly six vertebrae of which one includes left-hand strut **1111** and right-hand strut **1112.** Spines **1101,1102,1103,1104,1105,1106,** and **1107** are each an embodiment of the present invention, each having a structure concisely described with reference to **Fig. 12.**

Fig. 12 shows a chart **1200** with rows **1205** through **1275** that each correspond with one instance of a hyperstrut spine of the present invention. Each of the 11 cells in column **1280** contains a reference number of one of the left-hand struts, and the same-row's cell in column **1285** contains a reference number of a corresponding right-hand strut (i.e. of the same hyperstrut spine). Chart **1200** and this text include enough description to enable one of ordinary skill to identify all of the vertebrae relating to each spine described, within **Fig. 11** or **Fig. 13**.

Recalling that each hyperstrut spine has a left-hand acute angle about equal to j×20.9° + k×31.7° + m×36° + n×37.4°, the integers j, k, m, and n are given respectively in columns **1281, 1282, 1283,** and **1284.** The integers for the right-hand acute angles are similarly defined by the integers p, q, r, and s that are likewise given respectively in columns **1286, 1287, 1288,** and **1289.** Column **1290** indicates the count of each hyperstrut spine embodiment, and column **1291** indicates its regularity (with zero indicating nominal irregularity). Finally, column **1292** indicates the inter-strut angle between the two struts of each vertebra.

Row **1205** describes the structure of spine **1101,** indicating seven regularly-spaced vertebrae of which one includes struts **480** and **490.** (See mast **401** of **Fig. 11.**) Row **1205** further indicates that strut **480** is a left-hand strut that forms an acute angle of about 37° with its left-hand axis (i.e. axis **492**). Row **1205** further indicates that strut **490** is a right-hand strut that forms an acute angle of about 37° with its right-hand axis. The last cell in row **1205** indicates a primary angle (like angle **197** of **Fig. 1**) nominally equal to an acute angle of 63.4° (d=2).

Row **1210** describes the structure of spine **1102,** indicating six regularly-spaced vertebrae of which one includes struts **490** and **1111.** (See **Fig. 11.**) Row **1210**

further indicates that strut **490** is a left-hand strut that forms an acute angle of about 37° with its left-hand axis (i.e. axis **493**). Row **1210** further indicates that strut **1111** is a right-hand strut that forms an acute angle of about 21° with its right-hand axis. The last cell in row **1210** indicates a primary angle nominally complementary to an acute angle of 31.7° (d=1).

Row **1215** describes the structure of spine **1103,** indicating six regularly-spaced vertebrae of which one includes struts **1111** and **1112.** (See **Fig. 11.**) Row **1215** further indicates that strut **1111** is a left-hand strut that forms an acute angle of about 21° with its left-hand axis (i.e. axis **493**). Row **1210** further indicates that strut **1112** is a right-hand strut that forms an acute angle of about 21° with its right-hand axis. Note that the central mast **401** can be extended to a count of more than six by inserting additional instances of cells **600** and **700** just below the topmost instance of cell **500.** The last cell in row **1215** indicates a primary angle nominally equal to an acute angle of 36° (f=1).

Row **1220** describes the structure of spine **1104,** indicating six regularly-spaced vertebrae of which one includes struts **1131** and **1132.** (See leg **302** of **Fig. 11.**) Row **1220** further indicates that strut **1131** is a left-hand strut that forms an acute angle of about $j \times 20.9° + n \times 37.4° = 58.3°$ with its left-hand axis (i.e. axis **1142**). Row **1220** further indicates that strut **1132** is a right-hand strut that forms an acute angle of about $q \times 31.7° = 63.4°$ with its right-hand axis. The last cell in row **1220** indicates a primary angle nominally equal to an acute angle of 31.7° (d=1).

Row **1225** describes the structure of spine **1105,** indicating six regularly-spaced vertebrae of which one includes struts **1132** and **1133.** (See **Fig. 11.**) Row **1225** further indicates that strut **1132** is a left-hand strut that forms an acute angle of about 63° with its left-hand axis (i.e. axis **1141**). Row **1225** further indicates that strut **1133** is a right-hand strut that forms an acute angle of about $p \times 20.9° + s \times 37.4° = 79°$ with its right-hand axis. The last cell in row **1225** indicates a primary angle nominally equal to an acute angle of 79.2° (b=2,g=1).

Row **1230** describes the structure of spine **1106,** indicating six regularly-spaced vertebrae of which one includes struts **1133** and **1134.** (See **Fig. 11.**) Row **1230** further indicates that strut **1133** is a left-hand strut that forms an acute angle of

about 79° with its left-hand axis (i.e. axis **1143**). Row **1230** further indicates that strut **1134** is a right-hand strut that forms an acute angle of about q×31.7° = 63° with its right-hand axis. The last cell in row **1230** indicates a primary angle nominally equal to an acute angle of 79.2° (b=2,g=1).

Row **1235** describes the structure of spine **1107,** indicating six regularly-spaced vertebrae of which one includes struts **1134** and **1135.** (See **Fig. 11.**) Row **1235** further indicates that strut **1134** is a left-hand strut that forms an acute angle of about k×31.7° = 63.4° with its left-hand axis (i.e. axis **1142**). Row **1235** further indicates that strut **1135** is a right-hand strut that forms an acute angle of about 58.3° with its right-hand axis. The last cell in row **1235** indicates a primary angle nominally equal to an acute angle of 31.7° (d=1).

Referring now to **Fig. 13,** there is shown a triangular frame **1300** of hyperstruts in a partially exploded view. Frame **1300** includes multiple spines **1301,1302,1303,1304** of the present invention. Spine **1301** includes struts **1331** and **1332.** Referring now to **Figs. 12&13,** row **1250** indicates that spine **1301** includes six irregularly-spaced vertebrae. Row **1250** further indicates that strut **1331** is a left-hand strut that forms an acute angle of about 72° with its left-hand axis (i.e. axis **1341**). Row **1250** further indicates that strut **1332** is a right-hand strut that also forms an acute angle of about 72° with its right-hand axis (i.e. axis **1344**). The last cell in row **1250** indicates a primary angle (like angle **197** of **Fig. 1**) nominally equal to an acute angle of 60° (c=2).

Row **1260** describes the structure of spine **1302,** indicating nine irregularly-spaced vertebrae of which one includes struts **1351** and **1352.** (See **Fig. 13.**) Row **1260** further indicates that strut **1351** is a left-hand strut that forms an acute angle of about 31.7° with its left-hand axis (i.e. axis **1364**). Row **1260** further indicates that strut **1352** is a right-hand strut that forms an acute angle of about 31.7° with its right-hand axis (i.e. axis **1363**). Two of the nine irregularly-spaced vertebrae form part of the regular icosahedra **1388** affixed to the ends of leg **1385.** The last cell in row **1260** indicates a primary angle nominally equal to an acute angle of 60° (c=2).

Row **1270** describes the structure of spine **1303,** indicating eight irregularly-spaced vertebrae of which one includes struts **1353** and **1354.** (See **Fig. 13.**) Row

1270 further indicates that strut **1353** is a left-hand strut that forms an acute angle of about 37.4° with its left-hand axis (i.e. axis **1373**). Row **1270** further indicates that strut **1354** is a right-hand strut that forms an acute angle of about 37.4° with its right-hand axis (i.e. axis **1374**). The last cell in row **1270** indicates a primary angle nominally equal to an acute angle of 70.6° (e=2).

Row **1275** describes the structure of spine **1304,** indicating 6 irregularly-spaced vertebrae of which one includes struts **1355** and **1356** (in this example including the bottom icosahedron **1388** but excluding the top icosahedron **1388**). (See **Fig. 13.**) Row **1275** further indicates that strut **1355** is a left-hand strut that forms an acute angle of about 31.7° with its left-hand axis (i.e. axis **1361**). Row **1275** further indicates that strut **1356** is a right-hand strut that forms an acute angle of about 31.7° with its right-hand axis (i.e. axis **1362**). The last cell in row **1275** indicates a primary angle nominally equal to an angle of 60° (c=2).

Recall from the "summary" section above that the "fifth" embodiment described there recites an angle between struts of each vertebra that is nominally (equal to or) complementary to an acute angle of $b\times20.9° + c\times30° + d\times31.7° + e\times35.3° + f\times36° + g\times37.4°$, where b, c, d, e, f, and g are each an integer ≥ 0. Row **1275** describes such an embodiment, one in which b=d=e=f=g=0 and c = 2. Recall also that this "fifth" embodiment further requires that a uniform (total) number T of additional strut ends each bear against a corresponding one of the left-hand nodes, where T is at least 4 or 5. An examination of **Figs. 12&13** will reveal that the embodiment of row **1275** satisfies this recitation also, with T=5 (still excluding the top icosahedron **1388**).

Each of these 11 rows **1205** through **1275** describes a respective embodiment of the present invention. All 11 of these embodiments incorporate all of the features mentioned above relative to **Fig. 1** to the extent consistent with **Figs. 11-13.** In the embodiment of row **1205**, for example, strut **480** of **Fig. 11** incorporates surfaces **104,105** and all of the other features described above with respect to left-hand struts **180** of **Fig. 1.** The angles and structure shown in **Fig. 11** take precedence, however, and so it should be understood that the hyperstrut spine **1101** of this embodiment does not incorporate any inter-primary struts **107.** A review of **Figs. 11-13** will

reveal that the embodiments of rows **1220,1225,1230,1235,1250** each incorporate several basic inter-primary struts **107** each coupling to two primary nodes, but that the embodiments of rows **1205,1210,1215,1260,1270,1275** do not.

Referring again to **Fig. 13**, three nominally regular icosahedra **1388** are used for joining three legs **1381,1383,1385.** All of the nodes of leg **1381** are aligned on a corresponding one of six axes **1321,1322,1323,1324,1325,1326** as shown. "Ghost" elements **1390** (nodes and struts) are each drawn in dashed lines at each end of leg **1381** to show how a corresponding element in both icosahedra **1388** couples into the actual elements of the leg. Legs **1383** and **1385** also include ghost elements **1390** at each end, duplicating actual elements drawn elsewhere. All of the actual nodes of leg **1383** are aligned along a respective one of four axes **1341,1342,1343,1344.** All of the nodes of leg **1385** are aligned along a central axis (not shown) or a respective one of ten external axes **1361,1362,1363,1364,1365,1371,1372,1373,1374,1375.**

To further clarify the structure of frame **1300,** sub-structures **1394,1395,1396,1397,1398,1399** are shown that correspond with cells in **Figs. 14-19.** Leg **1383** is not broken down into cells, however. This is because almost all of the triangles formed by actual struts in leg **1383** are nominally 36°/72°/72°, 60°/60°/60°, or 108°/36°/36°. It is easy to distinguish these shapes visually in **Fig. 13**.

It has been mentioned that one advantage that can be gained by using geometries of the present invention is economy of scale. In **Fig. 13,** this is manifested in that the entirety of "hyper-triangle" frame **1300** can be assembled and fully triangulated as shown using only seven different (nominal) strut lengths, for use with a uniform type of node. Tower **300** of **Fig. 4,** in fact, can be assembled and fully triangulated as shown using only four distinct nominal strut lengths. Leg **1383** can be assembled and fully triangulated as shown with only three lengths, even including icosahedra **1388** affixed to each end. Leg **1385** can be assembled and fully triangulated as shown with only five lengths, even including icosahedra **1388** affixed to each end. More broadly, structures of the present invention preferably have a core (consisting of the claimed elements plus basic elements for full triangulation) such that all of their struts each have a length that is nominally included in a

predefined set consisting of at most 3 to 8 lengths, and more typically at most 5 to 7 lengths.

Referring now to **Fig. 14**, there is shown a complex cell **1400** nominally corresponding to sub-structure **1394** of **Fig. 13**. Four instances of cell **1400** occur in leg **1385,** two of them upside-down. Cell **1400** includes a top and bottom **1410** that are each a regular pentagon. Cell **1400** also includes 5 rectangular sides. An internal nexus point **1401** is slightly below the center point of cell **1400,** defining a pentagonal pyramid (inverted as shown) with 5 sides that are each an equilateral triangle. Nexus point **1401** also defines a pentagonal pyramid (upright as shown) with 5 sides **1420** that are each a 63.4°/58.3°/58.3° (isosceles) triangle. Nexus point **1401** also defines 5 irregular rectangular pyramids, one of which is shown, each having three isosceles triangles and one equilateral triangle.

Referring again to **Fig. 13,** it has been mentioned that leg **1385** includes four nodes (at nexus points **1401**) along a central axis of leg **1385**, and six such nodes if the entire icosahedra **1388** affixed to each end are included. **Fig. 14** clarifies how these nodes and the struts affixed to them are positioned. Such internally-positioned nodes are advantageous for lending stability to a hyperstrut. Leg **1385** is, in fact, a preferred embodiment of the present invention in which the (claimed) nodes and several additional nodes are all positioned exteriorly so as to form an oblong shape (i.e. leg **1385**) substantially resembling a tube having an elliptical cross section, further comprising several other, interiorly-positioned nodes that lend rigidity. A set of nodes form an "oblong shape substantially resembling a tube," as described herein, if a simple tube can be defined so that its exterior surface will intersect with substantially all nodes in the set. Such is the case with all of the legs **302,303,304,1381,1383,1385** mentioned above, and also with mast **401**.

Referring now to **Fig. 15,** there is shown another cell **1500** having a top and bottom **1510** that are regular pentagons. Cell **1500** occurs six times in leg **1385,** one of them nominally corresponding to sub-structure **1395.** Cell **1500** has ten sides **1520** that are each a 70.5°/54.7°/54.7° triangle (isosceles) as shown.

Fig. 16 shows yet another cell **1600** having a top and bottom **1610** that are regular pentagons. Cell **1600** occurs five times in leg **1385** (excluding the icosahedra

1388), one of them nominally corresponding to sub-structure **1396.** Cell **1600** has ten sides **1620,** each an equilateral triangle.

Fig. 17 shows a cell **1700** that occurs three times in leg **1381,** one of them nominally corresponding to sub-structure **1397.** Cell **1700** has a bottom and top **1710** that are each an equilateral triangle. Cell **1700** also has six sides **1720** that are each a 70.5°/54.7°/54.7° triangle (isosceles) as shown.

Fig. 18 shows a cell **1800** that occurs five times in leg **1381,** one of them nominally corresponding to sub-structure **1398.** Cell **1800** has a bottom and top **1810** that are each an equilateral triangle. Cell **1800** also has six sides **1820** that are each a 63.4°/58.3°/58.3° triangle (isosceles) as shown. Cell **1800** is the same as cell **600** of **Fig. 6,** oriented differently.

Fig. 19 shows a cell **1900** that occurs only once in leg **1381,** nominally corresponding to sub-structure **1399.** Cell **1900** has a bottom and top **1910** that are each an equilateral triangle. Cell **1900** also has six sides **1920** that are each a 116.6°/31.7°/31.7° triangle (isosceles) as shown.

Referring again to **Fig. 13,** it will be noted that four of the irregular pyramids with rectangular bases are not illustrated with any of the cells of **Figs. 14-19.** One of these cells would be adjacent to the axes of struts **1353&1354,** and its twin is just above it. These cells have four triangular sides, one equilateral, one 138.2°/20.9°/20.9°, and two 31.7°/69.1°/79.2°. Another of these cells would be adjacent to the axes of struts **1351,1352,** and its twin just above it. These cells have four triangular sides, one 70.5°/54.7°/54.7°, one 116.6°/31.7°/31.7°, and two 37.4°/63.4°/79.2°.

Fig. 20 shows a flowchart **2000** of the present invention including steps **2010** through **2040.** In step **2010,** at least 6 to 10 primary nodes are constructed so that each includes at least 1% metal by weight, the metal preferably being on or near bearing surfaces (like surface **104** of **Fig. 1**). Also during step **2010** a set of at least 6 to 10 similar vertebrae are assembled, each vertebra including one left-hand strut having a proximal portion and a distal portion, one right-hand strut having a proximal portion and a distal portion, and one primary node rigidly engaging the left-hand strut's proximal portion and the right-hand strut's proximal portion. Step

2010 is performed so that the primary nodes are each made to intersect a primary axis, so that the left-hand struts are all (nominally) parallel with each other, and so that the right-hand struts are all (nominally) parallel with each other.

In step **2020,** several left-hand nodes are each brought to bear against a respective one of the (left-hand struts') distal portions and each to intersect a left-hand axis that lies in a baseplane with the primary axis. This is performed so that this left-hand axis intersects each of the left-strut axes so as to form an acute angle therebetween about equal to $J\times20.9° + K\times31.7° + M\times36° + N\times37.4°$, where J, K, M, and N are each an integer ≥ 0.

Similarly in step **2030,** several right-hand nodes are each brought to bear against a respective one of the (right-hand struts') distal portions and each to intersect a right-hand axis that lies in a baseplane with the primary axis. This is performed so that this right-hand axis intersects each of the right-strut axes so as to form an acute angle therebetween about equal to $P\times20.9° + Q\times31.7° + R\times36° + S\times37.4°$, where P, Q, R, and S are each an integer ≥ 0.

In step **2040,** these nodes and struts are assembled into a triangulated structure using several additional struts so that each of the nodes couples to at least 3 struts that are not nominally coplanar. This is performed, typically using additional nodes also, so as to generate hypertriangle structures such as the hyperstrut legs **302,1381,1383,1385** described above with reference to **Figs. 3-19.**

All of the structures and methods described above will be understood to those skilled in the art, and would enable the practice of the present invention without undue experimentation. It is to be understood that even though numerous characteristics and advantages of various embodiments of the present invention have been set forth in the foregoing description, together with details of the structure and function of various embodiments of the invention, this disclosure is illustrative only. Changes may be made in the details, especially in matters of structure and arrangement of parts within the principles of the present invention to the full extent indicated by the broad general meaning of the terms in which the appended claims are expressed.